GREEN STURGEON
(Acipenser medirostris)

DRAFT

ERPP SPECIES DESIGNATION: Recovery "R"
FEDERAL STATUS: Threatened
STATE STATUS: California Species of Special Concern
RECOVERY PLAN(S): U.S. Fish and Wildlife Service, 1996

GENERAL INFORMATION

Distribution (Current and Historical)

Green sturgeon (*Acipenser medirostris*) have been recorded from the coastal waters of Mexico, the United States, and Canada. In North America, the green sturgeon's range in the ocean extends from the Bering Sea to Ensenada, Mexico. This range includes the entire coast of California. They have been found in rivers from British Columbia south to the Sacramento River in California. There is no evidence of the species spawning in Canada and Alaska, although they are caught in the Fraser and Skeena Rivers (Houston, 1988). They are found in the Columbia River (Moyle, 2002) and Willapa Bay in Washington (Langeness, pers. commun) and coastal rivers in Oregon (Emmet *et al.*, 1991). Within California, they have been recorded in the Sacramento/San Joaquin watershed, Eel, Klamath, and Trinity Rivers (Moyle, 2002). Their abundance increases gradually north of Point Conception.

Physical Description

Sturgeons, with their large size, subterminal and barbeled mouths, lines of bony plates on the sides, and shark-like tail, are among the most distinctive of freshwater fishes. Three species of sturgeon species were originally described, and this species was named *medirostris* or "middle snout" because the length of its snout was greater than one congeneric and less than another (Ayers, 1854). Green sturgeon have a dorsal row of 8-11 bony plates (scutes), lateral rows of 23-30 scutes, and two bottom rows of 7-10 scutes. The dorsal fin has 33-36 rays, and the anal fin, 22-28. This species is similar in appearance to the white sturgeon (*Acipenser transmontanus*), with which it co-occurs, except that its barbels are usually closer to the mouth than to the tip of the long snout. In addition, there is one large scute behind the dorsal fin, as well as one behind the anal fin, which are both lacking in white sturgeon. Body color is olive-green, with an olivaceous stripe on each side and scutes that are paler than the body. The common name, green sturgeon, is apt due to its distinctly green hue.

The Sakhalen sturgeon, which was once widespread in Japan, Korea, China, and Russia, is similar in body proportion and distribution of scutes to the green sturgeon. However, the former (*A. mikadoi*) is now considered a distinct species based on differences in the frequencies of three mitochondrial genes (Birstein et al., 1997; Birstein and DeSalle, 1998). It now occurs solely in the Tumnin River (Moyle, 2002).

Life History

The ecology and life history of green sturgeon have received comparatively little study because of the species' low abundance and low commercial and sport-fishing value. Adults migrate up the Klamath and Sacramento Rivers between late February and late July (Moyle, 2002). Their spawning period is from March to July, with a peak from mid-April to mid-June (Emmett *et al.*, 1991). The males and females spawn in deep, slow moving pools. The females lay thousands of large eggs, which are adhesive and settle into the spaces between the cobbles in the bottom of the river. The eggs hatch in seven days, and the larvae have a large yolk sack, swim near the bottom, and begin feeding after 10-15 days. Larvae hatched in the laboratory avoid light, indicating that they hide during the day and forage at night. The larva becomes a fully developed juvenile with a length of 74 mm FL at an age of 45 days (Deng, 2002). Juveniles captured above the Red Bluff diversion dam in the upper Sacramento River had grown to an average FL of 29 mm FL. This rate of growth is consistent with rapid growth of 300 mm in one year, and 600 mm within two to three years of juveniles in the Klamath River (Nakamoto *et al.*, 1995). Juveniles inhabit the estuary from 2-4 years, when they migrate to the ocean (Schaffter pers. commun.).

Green sturgeon travel extensively in the ocean, moving principally over the continental shelf prior to returning to fresh water to spawn (Moyle, 2002). Thirteen of 15 sturgeon tagged in the Sacramento River were captured to the north in estuarine and coastal waters (California Fish and Game, 2002). A northern migration is further supported by the prevalence of green sturgeon during the summer in the Columbia River estuary, Willapa Bay, and Grays Harbor (Adams *et al.*, 2002). Furthermore, green sturgeon with individually coded ultrasonic tags affixed to them in San Pablo Bay have been detected by tag-detecting electronic monitors situated in river systems in Oregon and Washington (Kelly, unpub. data). Individuals tagged in Willapa Bay, and identified by four monitors placed to record the estuarine entry and departure, resided in the estuary during most of the summer, yet exhibited rapid and frequent movements between other estuaries along the coast of North America (Moser, 2002). Five subadult (101-106 cm TL) and one adult (153 cm TL), carrying with ultrasonic tags, were tracked by boat for 2-16 h per day over periods ranging from 1-12 days (Kelly *et al.*, 2002, 2005). The four subadult fish remained within San Pablo Bay for the duration of their tracks; one moved well into Suisun Bay. The adult fish excited the bay and ocean within six hours of its release near Tiburon, California.

1. Graphical Component of Life History Model

A concerted program of research has been conducted over the past six years to describe the basic biology of the green sturgeon. The majority of the work has been performed in the laboratory, and has resulted in a description of the development of the species, the rates of egg hatch, growth of larvae, and growth of juveniles in water of different temperatures. More recently, field studies have been started to describe of the movements of the species within the Sacramento/San Joaquin watershed, during which tissue samples have been collected for genetic analysis. The latter have provided insight into the population structure of the species along the western coast of North America. Additional information must be collected for the diversity of inputs needed for an effective population viability model, which will predict the impact of environmental variations, both of natural and anthropogenic origin, on the species within California. Below is a conceptual model of the ecological perils confronted by the species that identifies risks (in italics) and suggests needed biological information (in bold) for the development of a highly predictive viability model (Fig. 1). The following factors may have a deleterious effect on green sturgeon populations in California: 1) high concentrations of pollutants, 2) decreased river flows, 3) high water temperatures, 4) excessive diversion of water to irrigation canals (and entrainment of juveniles), and 5) exorbitant fishing pressure on subadults and adults. Biological information needed for such a model to be useful include the: 1) the locations of spawning sites within the watershed and the environmental factors promoting reproduction at these sites, 2) knowledge of the impact of pollutants of various life history stages, 3) a record of the growth rate, age of reproductive maturity, and spawning periodicity of green sturgeon within the watershed, and 4) an estimate of the number of actively spawning adults within the watershed. The green sturgeon, which is historically an uncommon species, presents a formidable challenge to biologists in their quest to determine whether the size of the

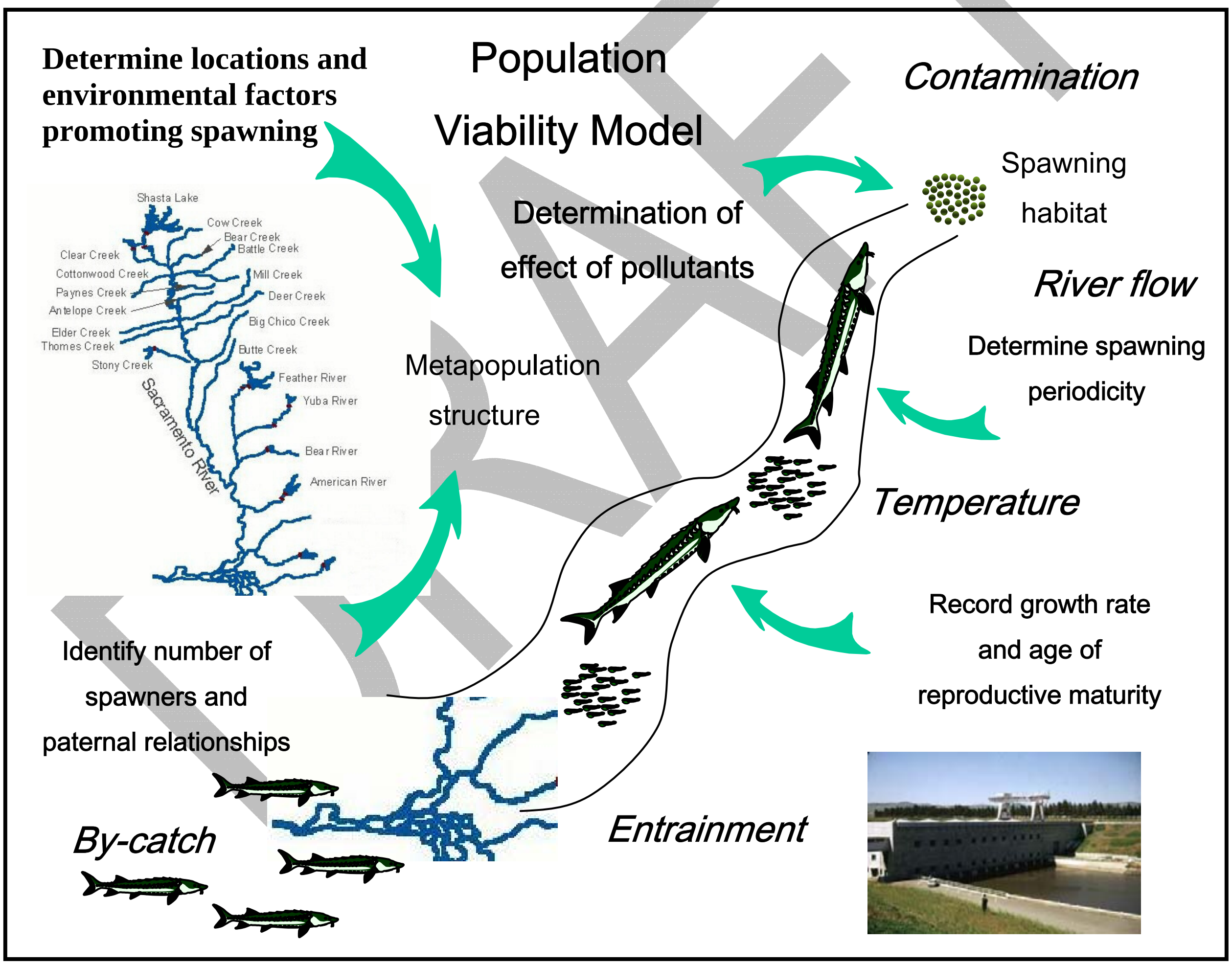

Figure 1. . Conceptual model of management study of green sturgeon in one river system in California, the Sacramento/San Joaquin watershed. The putative risks to the population of the species are italicized; the needed inputs to a population viability model are given in bold. Data is already available from multi year study to satisfy other inputs to model.

population is increasing or decreasing relative to its low historical levels of abundance in the rivers of California.

2. Narrative Component of Life History Model

BIOLOGY, ECOLOGY, AND STATUS

Biology

Fecundity

The fecundity of green sturgeon is known for adult females captured in the lower Klamath River. Female green sturgeon, ranging from 162 to 242-cm TL with a mean 196.7 cm TL, produce between 59,000-242,000 eggs with a mean of 142,000 (Van Eenennaam, et al., submitted). The fertilization rate of these green sturgeon eggs is 41.2% when exposed to pooled milt. The eggs are large, their maximum diameter being 4.3 mm (N=73), and appear to be less adhesive compared to white sturgeon eggs. The larval survival from hatching to metamorphosis are 94.3%. The newly hatched green sturgeon, which have a large yolk sack, are demersal and have a mean length of 13.7 mm. The larvae begin feeding at an age of 10-15 days, and a mean length of 14.0 mm. Metamorphosis into a fully developed juvenile is complete at an age of 45 days and a mean length of 74.4 mm. The larger size of the eggs and larvae, the lower adhesiveness of fertilized eggs, and the bottom-oriented, demersal behavior of the larvae suggests that the species selects a different microhabitat within the river for spawning than the white sturgeon (Deng *et al.*, 2002), such as deep pools with large cobble on the bottom (Moyle, 2002).

Reproduction

Green sturgeon are seasonal breeders. Their spawning period is March to July, with a peak in mid-April to mid-June (Moyle *et al.*, 2002). They are known to spawn in two California Rivers, the Klamath and Sacramento Rivers. Adults are captured by gillnet within the Klamath River downstream of a natural barrier to movement, Ishi Pisha Falls (Rkm 107). Adults are thought to spawn in a pool named the Sturgeon Hole (Rkm 96) upstream of Orleans, where individuals are observed leaping and performing other behavioral patterns, which can be interpreted as courtship during spring and early summer (Moyle, 2002). Larvae and juvenile green sturgeon are captured yearly in the rotary-screw traps, deployed at Big Bar (Rkm 80) on the Klamath and in the Willow Creek trap (Rkm 40) on the Trinity River, a tributary of the Klamath. The frequency of small juveniles, indicative of recent reproduction, captured at both traps is highest in July (Healy, 1973). Two small green sturgeon juveniles were also collected in the lower 10 km of the Salmon River, a tributary of the Klamath, during October 1996.

Since 1981, adult green sturgeon have been observed during late spring from Patterson riffle (Rkm 374) to immediately below the Red Bluff diversion dam (Rkm 391) in the Sacramento River [Brown, 2002]. They have most often been observed in the pool downstream of the RBDD. Larvae and small juveniles were recorded during late spring from 1995-2001 at the diversion dam and from 1986 to 2001 at the Glenn-Colusa irrigation pumping plant (Adams *et al.*, 2002). The larvae were inferred to be green sturgeon because 136 individuals, collected at that site and raised to identifiable size, were later identified to be that species (Beamsderfer and Webb, 2002). Artificial substrate mats were placed between 379-426 Rkm between late March and Mid July 2001 in order to collect the eggs of green sturgeon (Brown, 2002, 2003). Two green sturgeon eggs, identified by genetic analysis (Josh Israel, pers. commun.), were collected with mats immediately below the diversion dam (Rkm 391) on 14 June 2001. The date of spawning can be assumed to be 11 June 2001 based on the known rate of egg development (Brown, 2002). Larval nets were used in five locations ranging from 391-424 Rkm along the river, and one green sturgeon larva was collected with a net at Bend Bridge (Rkm 415) on 13 July 2001[Brown, 2002, 2003]. The larva's stage of development was consistent with it having hatched out 13 days earlier, and assuming an incubation period of six days, spawning occurring on 24 June 2001. Both of these dates lie within the period of late April through July, inferred for spawning based on the catch of juvenile green sturgeon captured by rotary screw traps at the Red Bluff Diversion Dam (Rkm 391)from January 1995 through June 2000 (Brown, 2002).

Spawning in deep reaches of the headwaters of the Sacramento River is consistent with the timing green sturgeon upstream migrations in other rivers. Green sturgeon, tagged with radio transmitters, entered the Rogue River, Oregon, during April-June, spent the summer and early autumn months in deep (>5 m), low-gradient reaches or off-channel coves in the Rogue River, Oregon, and outmigrated during late fall and winter (Erickson *et al.*, 2002). Individuals do not spawn during successive years, but once every two to four years (Erickson and Webb, 2005). Sturgeon carrying transmitters migrated from 17-105 Rkm upriver, indicating that spawning occurs along the entire length of the river.

The majority of green sturgeon, tagged with both ultrasonic and radio tags, remained within the Klamath River in deep pools during summer for up to 170 days (Turo *et al.*, 2004). Tagged sturgeon exhibited four distinct movement patterns: 1) an upstream spawning migration during spring, 2) an early summer outmigration of a few individuals, 3) summer holding of the majority of individuals within deep pools, and 4) a fall outmigration in response to the first major rainfall of the season (Belchik, 2005). Furthermore, adults have been recorded by video in putative spawning reaches of the middle Klamath and Salmon Rivers (Soto, 2005).

Development (Fish Swimming Ability and Growth)

Juvenile green sturgeon have rapid growth rates and high oxygen consumption rates, relative to other sturgeon species (Mayfield and Cech, 2004). Their consumption of food, growth, and food conversion efficiency generally increase with temperature between 11° C and 15° C, but stay constant between 15° C and 19° C. Oxygen consumption, activity rate, and ventilatory frequency generally increase, while swimming performance decreases with temperatures from 19° to 24° C. Their bioenergetic performance is optimal between 15° C and 19° C, when feeding on either full or reduced rations.

Ecology

Environmental Tolerance by Life Stage

The survival to hatch at constant incubation temperatures ranging from 11.0-26.0° C was examined for green sturgeon in laboratory studies (Van Eenennaam *et al.*, 2005). Temperatures ranging from 11.0-17.0º C were optimal for hatching and developing embryos. Water temperatures between 17.5-19°C resulted in less, but satisfactory hatching success, but the percentage of abnormal embryos increased within this temperature range.

The impact of constant temperatures of 18, 20, 22, 24, 26 and 28°C on survival of hatched larvae through yolk-sac resorption was examined in laboratory studies with larvae (Linares-Casenave *et al.*, 2005). Progeny from different females exposed to temperatures ranging from 18-24°C exhibited nearly 100% survival to stage 45 of development. The weight, length, and caloric content of larvae at stage 45 did not exhibit significant changes within the prior-mentioned temperature range. Temperatures ranging from 24- 26°C resulted in either a slight (non-significant) or a significant decrease in survival, depending on progeny, whereas temperatures above 28° C were lethal to all larvae, irrespective of progeny. The percentage of abnormalitieis was significantly higher in the range from 22-25°C (21-36%), compared to 18-24ºC (1-2%) [Lineares-Casenave *et al.*, 2005]. The most prominent abnormality was a forward bending of the body (lordosis) caused by the flexure of the notochord.

The effects of time of day and water temperature on the acute physiological stress response were investigated in young-of-the-year green sturgeon (Lankford *et al.*, 2003). Sturgeon were exposed to two types of stress, a 1 min exposure to air during the day and night after acclimation to water of either 11º or 19°C. The plasma concentrations of cortisol, lactate, and glucose were measured for blood collected from sturgeon before and after exposure to these stresses. The concentrations of cortisol and lactate were higher for fish that were stressed at night than during the day. For fish acclimated at 11ºC, the duration of the stress response was extended longer than at 19°C. These studies indicate that the physiological response of green sturgeon varies with time of day and water temperature.

Environmental Releasers of Reproduction

In the Klamath River, spawning takes place in deep, fast water. Adults are captured by gillnet within the Klamath River downstream to a natural barrier to movement, the Ishi Pisha Falls (Rkm 107). The substrate here is likely large cobble, but it can range from clean sand to bedrock. Eggs are broadcast and externally fertilized in fast water, sink to the bottom and settle between cobbles at depths exceeding 3 m (Emmett *et al.*, 1991).

In the Sacramento River, spawning takes place in the mainstem above and below the Red Bluff diversion dam (Rkm 391). In a study aimed at identifying the spawning area of green sturgeon (Brown, 2002, 2003), artificial substrate mats were placed between 379-426 Rkm for 15 weeks between late March and Mid-July 2001. The mats were examined twice weekly for the presence of sturgeon eggs, and two eggs, identified as green sturgeon from genetic analysis, were found on substrate mats immediately below the Red Bluff Diversion Dam (Rkm 391). Larval nets were deployed at five locations from 391-424 Rkm between late June and mid-July for a total of 21 hrs to capture sturgeon larvae, and one larva was collected at Bend Bridge (Rkm 415). Young green sturgeon have also been identified downstream in the mainstem, indicative of spawning (Fry, 1973; Moyle *et al.*, 1995). Larvae also have been found in salmon outmigrant traps, deployed in the lower Feather River, indicating that this is also a spawning site (Moyle, 2002). Some spawning may also occur in the lower San Joaquin River, because juvenile green sturgeon have been captured at Santa Clara Shoal, Brannan Island State Recreational Area, Sacramento County (Radke, 1973). The temperatures vary from 10° to 15° C over this time period, and these thermal conditions are similar to those existing from March to July in the Klamath River, where green sturgeon spawn (Emmett *et al.*, 1991).

Trophic Status

The green sturgeon is a secondary consumer, feeding upon invertebrates and small fish (Moyle, 2002).

Feeding Strategy

Juveniles and adults are benthic feeders, a foraging tactic consistent with their subterminal mouth and labial barbels. They largely feed on sessile invertebrates, but may also take small fish (Moyle, 2002). Juveniles in the San Francisco Bay feed on opossum shrimp and amphipods (Radtke, 1966). Adults caught in Washington had fed mainly on sand lances (*Ammodytes hexapterus*) and callianassid shrimp (Foley, pers. commun.). Green sturgeon in the estuary of the Columbia River feed on anchovies and clams (Wydoski and Whitney, 1979).

Spatial Distribution and Timing of Occurrence

Green sturgeon travel up the Klamath River between late February and late July and spawn from March to July, with a peak in reproductive activity from mid-April to mid-June. Adult males captured in the Klamath ranged from 139-199 FL with 90% of the males being 15-28 years old. One hundred and fourteen males, sampled between 1999-2003 on the Klamath River, were fully mature, the testicular cysts containing differentiated spermatozoa; two males had cysts with regressed testis and residual spermatozoa in the cysts, indicative of recent spawning (Van Eenennaam *et al.*, submitted). Two males, 115 and 143 cm FL and aged 10 and 15 years respectively, were immature as evident from only gonial cells being enclosed within the cysts. The 82 adult females, from 151-223 cm FL and from 19-28 years old, were in pre-ovulatory condition, indicating readiness to spawn. The slope of a regression of polarization index, a morphological criterion of egg ripeness, as a function of distance, at which the female was captured from the river mouth, did not differ significantly from zero. This relationship is consistent females making a single spring spawning migration upstream in the Klamath River. The females are able to hold the eggs at this advanced stage of maturation until they reach the desired spawning grounds, which may be multiple reaches within the river. Adult green sturgeon enter the San Francisco estuary in late February (Moyle, 2002). It is likely that spawning occurs within the mainstem of the Sacramento above and below the Red Bluff diversion dam (see above for more detail).

The eggs of green sturgeon hatch after 176 h at a temperature of 15.7° C. The larvae with a mean length of 13.7 mm TL absorb their yolk sac and begin feeding at a length of 24.0 mm after 10-15 days. They complete metamorphosis into a juvenile of a mean length of 74.4 mm at 45 days in water with a rearing temperature of 18.5° C (Deng *et al.*, 2002). These rates of development, determined in the laboratory, may vary in relation to the local temperature regime of the river. The juveniles appear to migrate toward the estuary before the end of their second year, primarily during summer and fall (Emmett *et al.*, 1971). In the Klamath River, the majority of juvenile sturgeon migrate downriver at 30-66 cm TL, when they are 1-3 years old, while some outmigrate at a smaller size as one-year olds. The juveniles spend 1-4 years in the river and estuary, reaching a size of 70 cm TL. Males spend 3-9 years at sea, females 3-13 at sea before returning to the estuary (Nakamoto *et al.*, 1995).

Individuals tagged by the California Department of Fish and Game have been recaptured off Santa Cruz, California, in Winchester Bay on the Southern Oregon coast, at the mouth of the Columbia River, and in Gray's Harbor (Chadwick, 1959: Miller, 1972). Individuals carrying individually coded ultrasonic tags have been detected by electronic monitors in Willapa Bay and the Columbia River in Washington (Kelly, pers. commun.). Subadults and adults have been captured during California Fish and Game surveys during the summer and fall (Kogut, pers. commun). Individuals carrying ultrasonic tags have been tracked throughout the estuary (Kelly, 2002). Yet genetic variation indicates that there is more similarity between green sturgeon from the Sacramento and the Columbia River than the Klamath River, which is closer to the former river (Israel *et al.*, 2004).

The frequency of spawning and the intervals between spawning migration are not known for certain, although one would anticipate that a long-lived species would be iteroparous. Based on their taxonomic affinity, spawning is thought to occur every five years (Tracy, 1990). However, small, darkly pigmented atretic follicles were not readily observed in the ovaries of the post-spawned females captured in the Klamath River, whereas these distinctive "salt-and-pepper" ovaries can be seen in white and Atlantic sturgeon, which are iteroparous. This apparent absence of pigment may be because the olive-green to brownish pigment of green sturgeon oocytes breaks down more quickly than in oocytes from the other species, or the large oocytes ovulate and are released more rapidly than from the other species (Van Eenennaam *et al.*, submitted). Recently, spawning individuals with coded ultrasonic tags affixed to them have returned after 2-4 years to the Rogue River, Oregon (Erickson and Webb, 2005), which indicates a spawning peridocity for females of less than five years.

Ongoing research aims at determining spawning periodicity by examining the composition of the individual growth rings (Allen, pers. commun.). The movement from salt to fresh water results in a change the strontium to calcium ratios in the calcium-carbonate otoliths of anadromous fish (Elsdon and Gillanders, 2003). The concentration of strontium is low in freshwater and much higher in seawater, and the proportion of strontium to calcium in the growth ring will increase as the fish makes its upstream spawning migration in fresh water (Bath *et al.*, 2000; Thorrold and Shuttleworth, 2000). Green sturgeon, carrying long-term (3-5 year duration) coded ultrasonic tags, will also be detected on successive spawning migrations by automated monitors currently deployed at the junctions between the mainstem and each major tributary of the Sacramento River (Kelly, pers. commun.).

Key Factors in Completing Life Cycle

Green sturgeon are long lived, and thus do not need to make upstream migrations every year. Hence, their migration can be timed to when environmental conditions are optimal such as during years of high precipitation. Once adults have spawned, the development and growth of the eggs and larvae are a function of water temperature. Excessively elevated local water temperatures could inhibit development and slow growth of juveniles. It is possible that juveniles can also be trapped in water diversions for farmland irrigation along the length of the river. Once within the estuary, juveniles might accumulate pollutants such as methyl-mercury that are concentrated by the filter feeders and scavengers in their diet.

Species Ecological Functions

This species is a secondary consumer, neither at the bottom or top of the food chain. For this reason, it is unlikely that a reduction in its abundance will have strong bottom-up or top-down influences on the abundance of other species. Furthermore, members of the species are relative rare, and hence have less impact upon removal on other tropic levels in the ecosystem.

Status

Historical and Current Population Status

There are time series of population size based on sampling green sturgeon in the Klamath River and San Pablo Bay. In the Klamath River, the Yurok tribal fishery has recorded the number of adults captured by gill net and catch-per-unit (CPU) effort per year during their migration upriver to spawn. These records are available since 1984, and the same gear has been used over time with little change in catch regulations. The number of individuals caught ranged from 108 individuals during 1995 to 417 in 1993. In order to identify any change in population size over time, a regression analysis was performed on logarithmically transformed catch and CPU from April and May over a period of 17 years from 1984 to 2001 (Adams *et al.*, 2002). The slopes of the two resulting regressions were small, 0.031 and 0.001, and were not significantly different than zero. Histograms of the sizes of adult fish captured during April and May of recent years are roughly normally distributed with no discernible decrease in the mean size of individuals captured, an indicator that fewer spawning adults exist in the population. The latter is a symptom of excess fishing pressure.

California Fish and Game performs the only non-harvest estimate of the population size of green sturgeon. Their estimate is obtained incidental to monitoring the size of the white sturgeon population in San Pablo Bay. They estimate population size by marking fish and recording the proportion of recaptured fish with marks later captured in trammel nets. Population surveys have been conducted since 1954, but since 1990 sampling has been carried out for two year intervals, discontinuing for the same period before starting again. The size of the green sturgeon population is estimated indirectly by multiplying the ratio of legal size green sturgeon to legal-size white sturgeon caught in the tagging program by the legal-size white sturgeon population estimate. This indirect method is used because tagged green sturgeon have yet to be recaptured, a consequence of the low sample size (233 individuals). The estimates of green sturgeon abundance ranged from 175 during 1993 to 8,421 during 2001. Despite the anomalously large estimate in 2001, a regression of green sturgeon abundance versus time had a small slope (b=0.029) that did not differ significantly from a slope of zero. The mean FL of green sturgeon captured in San Pablo Bay remained near 100 cm FL from 1954 to 2001, also indicating that fishing pressure is not impacting the local population. However, the number of green sturgeon inferred to occupy the bay may not be a true population size because the individuals within the bay may comprise a small fraction of the population still within the oceanic environment.

HABITATS, PROCESSES, STRESSORS, AND LINKAGES

Habitats

Habitat Attributes during Various Life Stages

Adult green sturgeon migrate up the Klamath River from late winter to spring to spawn in deep pools near the headwaters. The eggs develop into larvae during late spring and early summer, a time when the water temperature in the river remains low in response to the input of water from melting snow. Furthermore, water release from Shasta Dam is regulated to maintain daily temperatures below 13.3º C to facilitate the incubation of eggs of spawning winter-run chinook. The daily temperatures of the water above the Red Bluff Diversion Dam, where a larva was collected, ranged between 10.7-15.8° C during spring; the daily water temperature below the dam, where eggs were collected, ranged from 8.3-15.1º C (Brown, 2002). Larval survival could be impeded if rivers heat above 17° C, the temperature at which laboratory tests indicated abnormal larval development begins (Van Eenennaam et al., 2005). Little information is available on timing of the outmigration of juveniles from the Klamath and the underlying water conditions.

In the upper Sacramento River, the flow of water and its level is dependent on the release of water from the Shasta and Keswick dams at the Lassen and Keswick reservoirs. The releases from the Shasta dam are regulated to maintain a temperature at or below 13.3º C to ensure successful incubation and hatching of eggs from winter-run chinook salmon (Brown, 2002). Until the reservoirs are full, the rate of water release is low, increasing only slightly during rains and rapid melting of the snows in the surrounding Cascade Mountains. The flows are generally 169 m^3/ in the winter, reaching 1,415 m^3/s during flood events (Brown, 2002). Under these conditions, adult green sturgeon can move upstream and spawn in deep pools in the mainstem of the Sacramento River. Late in spring (May 15), a series of gates are closed at the Red Bluff diversion dam, permitting water to collect within a temporary reservoir to produce a head of pressure that permits water to pass into irrigation canals leading to farmlands. Flows from May through September range from 283-425 m^3/s (Brown, 2002). Large aggregations of green sturgeon have been observed in the pool below the diversion dam during May and June after the gates are closed (Brown, 2002). It is unknown whether a high proportion of the late migrating green sturgeon stay here to spawn or move downstream to enter other large tributaries such as the Feather River. The eggs of these sturgeon hatch and larvae develop during early summer, and it is unlikely that their development is impeded as temperatures are kept low within the river to enable winter-run chinook salmon to spawn successfully. Adults, tagged in San Pablo Bay, will now be recorded during their upriver migration by tag-detecting monitors, equipped with temperature loggers, situated at the mainstem and tributaries of the river and large pools above the diversion dam (Kelly, pers.commun.). Water temperatures are not high from May to August when juveniles are caught in the fyke traps at the Red Bluff Diversion Dam (Rkm 391) and the Glenn-Colusa Irrigation District (Rkm 330).

Interactions of Spatial and Temporal Patterns

Green sturgeon are long lived and thus can select optimal conditions for their upriver migration. They appear to time their upriver migration to the onset of the winter rains, remain in deep pools during the summer, and emigrate with the onset of the winter rains during the following year. The eggs and larvae develop during spring and summer, a time during which insects are common within the river system. The environmental factors underlying the down river migration of juveniles have yet to be identified as those factors underlying the immigration of subadults to the San Francisco Estuary and emigration of adults into the ocean environment.

Historical Habitat Alterations

Unlike the past, water is now being diverted for agricultural use and being hindered from flowing down the Klamath River. The absence of drainage from melted snow in the river increases the ambient water temperature. Larval survival could be impeded if rivers heat above 17° C, the temperature at which laboratory tests indicated abnormal larval development begins (Van Eenennaam et al., 2005). The hatching of eggs and development of larvae could be inhibit if the temperature of the rivers exceed 17° C, the temperature limit at which laboratory tests indicate that hatching success is high and larval development normal (Van Eenennaan *et al.*, in press). Water temperatures have yet to be recorded at spawning sites during normal flows and those during periods of water diversion.

In the past, water flowed throughout the mainstem of the Sacramento River, unimpeded from tributaries originating in the Cascade and Sierra Nevada Mountains. The water flow increased during periods of rain and when snow melted on the mountains. The temperature of the river, thus, remained low during spring and early summer. However, the presence of three dams have changed the normal hydrology of the river. In the upper Sacramento River, the flow of water and its level is dependent on the release of water from dams at the Lassen and Keswick reservoirs. Until the reservoirs are full, the rate of water release is low, increasing only slightly during rains and rapid melting of the snows in the surrounding Cascade Mountains. The temperature of the water within the river is maintained <13.3° C, which is optimal for salmon upmigration and spawning, by drawing water from increasing water depths in the reservoir to compensate for higher temperatures within the river. Under these conditions, adult green sturgeon can move upstream and spawn in deep pools within the mainstem of the river.

During late spring, a series of gates are closed at the Red Bluff diversion dam, forcing water to collect in a temporary reservoir that produces a head of pressure that permits water to flow through a series of irrigation canals leading to farmlands. At this time, some water is permitted to pass through a shallow race way, through which salmon can bypass the diversion and migrate upstream. However, it is believed that green sturgeon can not pass this passage. Large aggregations of green sturgeon have been observed at this time in the pool below the diversion dam. It is unknown whether all late migrating green sturgeon remain within this pool to spawn or move downstream to enter other large tributaries such as the Feather River

Processes

Critical Processes Affecting Species

The frequency and timing of rainfall are likely to affect the distribution of green sturgeon in the rivers of California. The increase in water flow may stimulate individuals in the coastal waters and estuaries to start migrating up coastal rivers. Fewer individuals may move upstream during dry years than wet years. In the Sacramento River, the timing of the flows may be critical to number of sturgeon migrating upstream. More adults may reach pools above Red Bluff and below the Lassen Dam when rains occur during late fall and winter, before the diversion dam impedes the flow of water within the river, than when rains arrive later in the season, continuing through April. Rainfall at this time may inhibit the upstream migration of individuals, who become blocked by the diversion dam. These adult sturgeon either remain in the pool below the dam or disperse into the tributaries of the river near the dam.

The temperature within the river affects the survival of eggs and larvae of green sturgeon. The survival of young is likely higher when the waters are cool during spring and early summer from the melting snow in the mountains. Any diversion of this cool water may result in the waters warming within the river, and this may reduce the survival of young within the river. The waters within the Sacramento are kept cool by regulating the outflow from the dams, and this likely ensures that the survival of eggs and larvae is high within the river.

Species Function in Community Food Web

The green sturgeon is a secondary or tertiary consumer, which feeds in benthic prey. It is not an abundant species, particularly in relation to the white sturgeon, and likely its rate of foraging has negligible impact on the abundance of its prey.

Stressors

Significant Stressors Affecting Species and Population Status

The rainfall in California varies greatly between years. The amount of the rainfall determines to which reaches the sturgeon can migrate within the mainstem and tributaries of the Klamath and Sacramento River. The timing of the rains determines the environmental conditions under which the eggs and juveniles develop within the river. Yet the green sturgeon is adapted to this environmental variability. Firstly, it is a long lived species, which can spawn repeatedly. Female and male sturgeon, captured in the Klamath River during April-July over a period of five years (1999-2003), ranged from 16-40 and from 14-32 years old, respectively (Van Eenennaam *et al.*, submitted). The oldest females are potentially capable of spawning 4.8 times per lifetime, given they spawn every five years (Tracy, 1990). However, if the recent tagging studies indicate that females may spawn every 2-4 years (Erickson and Webb, 2005)., then the potential number of spawning events per lifetime would increase. Sturgeon have been detected returning to the river to spawn after shorter intervals of two years in the Rogue River (Erickson, 2005). Secondly, females produce many eggs per spawn. The fecundity of individuals increases with size, ranging from 59,000 to 343,000 eggs. Thirdly, individuals of the species migrate over extensive geographic areas, and can choose multiple rivers, in which to spawn depending on their quality. These three characteristics permit individual of the species to spawn successfully, despite when these environmentally dynamic river habitats provide occasionally provide conditions suitable for spawning.

The population of green sturgeon does not appear to be declining in California waters. One indicator of population status is the rate of capture over time. However, there is no fishery targeting the species due to the inferior quality of the flesh. Green sturgeon are harvested almost entirely as bycatch in fisheries or sampling regimes directed at other species such as salmon, white sturgeon, and groundfish. Green sturgeon are harvested by the Yurok and Hoopla Indian tribes while fishing with gill nets for salmon, and are targeted after the salmon run, during May-June-July. The harvests have varied substantially from 136-451 individuals per year from 1985 to 2001, but have neither significantly increased nor decreased over this period (Adams *et al.*, 2002; Beamsderfer and Webb, 2002). The mean total lengths of the sturgeon captured per year has varied from 160 to 180 cm TL, but has not decreased significantly with time, as would be expected if impacted by high adult mortality due to fishing pressure. The health of the population is also evident from the size and age composition of green sturgeon caught per year. The distribution of these would be truncated if there were excessive subadult and adult mortality (Beamsderfer and Webb, 2003). The size and age distributions of female and male sturgeon, captured during 1999 and 2000 by the Yurok Indian Tribal Fishery, were distributed normally over a wide range, and this is consistent with slow maturation and a constant rate of mortality with increasing size and age (Van Eenennaam *et al.*, 2001).

Limiting Factors

The survival to hatch have been examined at constant incubation temperatures from 11-26°C in laboratory studies (Van Eenennaam *et al.*, 2005). Temperatures of 17-18°C are likely the upper limit of the thermal optima for green sturgeon embryo development, wherein the hatching success and normal development are not affected by waters below this temperature. 17.5-22°C were suboptimal as a reduced number of embryos developed normally and hatching success decreased at 20.5-22^{o}C. Malformed and incomplete cleavage was observed at the highest temperature and no embryos survived to gastrulation. Although some embryos at temperatures from 23-23.5°C passed through the initial cleavage stages only a few reached neurulation and all died before hatch.

The impact of constant temperatures of 18, 20, 22, 24, 26 and 28°C on survival of hatched larvae through yolk-sac resorption was examined in laboratory studies with green sturgeon larvae

(Linares-Casenave *et al.*, 2005). Temperatures above 26 °C were lethal to all larvae, irrespective of progeny. Temperature had a significant effect on the incidence of abnormal larvae. The typical abnormality due to temperature treatment observed in larvae was forward bending (lordosis) of the notochord. Temperatures ranging from 22-28°C had significantly higher numbers of deformed larvae, compared to lower temperatures. Even slight lordosis precludes larvae from normal straight forward swimming. Therefore, temperatures above 20°C may be detrimental to larval green sturgeon at yolk-sac and larval survival to metamorphosis.

Thermal stress in green sturgeon larvae was monitored on the basis of heat-shock protein (hsp) expression in newly hatched larval sturgeon exposed to a range of water temperatures from 18-28°C during yolk-sac absorption (Werner *et al.*, 2003; Werner *et al.*, 2005). Hsps are intracellular proteins important in protecting organisms against the cytotoxic consequences of protein denaturation and play a major role in thermo-tolerance and thermo-protection. Hsp expression and abnormal development increased significantly in larvae exposed to 22°C and above. Significant differences were observed between the two progenies. The rate of abnormalities effected by temperature was significantly lower in Progeny II than in Progeny I larvae (by 10-20%). In larval groups exhibiting elevated levels of several hsps, mortality and abnormal larval development generally increased. However, the intensity of the hsp response, in particular that of protein families hsp60 and hsp90, was indicative of better protection against and more tolerance of high water temperatures. Strong differences in temperature tolerance between two green sturgeon progenies appear to be due to genetic differences leading to earlier and more intense induction of several heat-shock proteins and therefore, better protection against high water temperatures.

The growth rates of post yolk-sac larval to early green sturgeon were measured at three elevated, temperature regimes, 19° C, 24º V, and alternating 12 h at 19º C and 12 h at 24° C (Allen *et al.*, 2002). Growth was more rapid and the resulting total lengths were longer when individuals were raised in water 24º C than in water of the lower temperature as well as alternating high and low temperatures. Thus, elevated and cycling temperatures in this range do not limit growth of juveniles with abundant food and oxygen.

Specific growth rates were calculated for young-of-the-year green sturgeon at temperatures elevated 2° and 4º above the ambient temperature with or without hypoxia, defined as 50% and 75% of oxygen saturation in water. An elevation of temperature alone did not influence the rate of growth, but an elevated temperature and low oxygen concentration resulted in a statistically significant slowing of the rate of growth (Wunderlich and Crocker, 2005). Thus, while sublethal temperatures alone do not reduce growth, the combined effect of elevated temperature and hypoxia do inhibit growth. Thus, it is essential to ascertain whether such conditions exist in the upper reaches of the Sacramento river because they can reduce the growth of young-of-the-year green sturgeon. In addition, larval green sturgeon showed variable foraging effectiveness on four substrates, rocks, cobble, sand, and a flat surface, and these likely contributed to different growth rates for the surfaces, 2.3%, 1.1%, 1.8%, and 2.3% body weight per day, and rates of mortality, 7%, 43%, 11%, and 0%, for the four surfaces (Nguyen and Crocker, 2005).

Young-of-the-year suffered a mortality rate of 100% when reared in salinities of 0 and 1 ppt, 13% mortality when in water of 3 ppt, and 28% mortality when in water of 5 ppt (Arce and

Crocker, 2003). The mean rates of growth for the surviving young raised in water with salinities at 3 and 5 ppt were 5.87% and 6.12% of their body weight per day. Thus, juveniles can survive when exposed to saline environments. The salinity tolerance of juvenile green sturgeon increases with size and age. One-hundred percent of the juveniles survived when exposure occurred 140 days after hatching (Allen *et al.*, 2003).

Numerous metal species have been found in the waters and sediments of San Francisco Bay. These metals have numerous documented effects on fish biochemistry, metabolism, osmoregulation, swimming performance, reproduction, and larval fish growth and survival (see following reviews: Heath, 1995; Rand, 1995). Mercury and specifically methylmercury has numerous documented effects on fish health. Exposure to sublethal concentrations of this organo-metal compound range from immuno-compromise, poor motor control, decreased growth, and most recently to endocrine disruption. Current research is ongoing examining the effects of methylmercury (MeHg) on green sturgeon via three routes of exposure; aqueous exposure to water hardening eggs, larval injections, and dietary exposure of MeHg in juvenile green sturgeon.

Linkages

Process and Stressor Linkages to Life Stage, Season, and Habitat

Variable rainfall and temperature are likely the variables, which have maximum impact on the reproductive success of the green sturgeon. Any alteration of the river producing an ambient water temperature higher than normal, which is a result of drainage from the melting of the snowpack, may reduce the rate of survival of eggs and larvae. There may be some mortality to juveniles due to diversion of water from the mainstem for agricultural use. However, the green sturgeon is well adapted to thrive in this dynamic habitat because of its long life, iteroparous mode of reproduction, high fecundity, rapid growth of eggs, larvae, and juveniles, and its ability to migrate over long distances along the coast.

UNCERTAINTIES

Uncertainties

Effectiveness of Past and Current Field Sampling

One of the most important time series of catch data are the records of the Yurok and Hoopla Tribes of the catch of green sturgeon from 1985-1999 in the Klamath River. Sampling for sturgeon was only carried out from March-April, when salmon migrate upstream within the river. The catch is a minimum estimate of the number of sturgeon migrating up the river –adults may have moved up the river before or after this period. The value of this sample lies in inter-annual comparisons of the abundance of spawning adults in the river system.

Green sturgeon also have been captured during periodic stock assessments by the Department of California Fish and Game in San Pablo Bay (Schaffter and Kohlhorst, 1999). Catch was first recorded in 1955, then recorded twice in the late 1960s, once in the mid and once in the late 1960's, and then for two year periods, each separated a hiatus of two years, from the mid 1980s to the early 2000s. So few green sturgeon have been marked during these surveys that no tagged individuals have been subsequently captured. Hence, the population size of the species can not be estimated directly for the bay. For this reason, the size of population of green sturgeon has been calculated by multiplying the fraction of green sturgeon to white sturgeon captured times the population estimate of the white sturgeon, determined on the fraction of marked versus non-marked white sturgeon captured subsequently. This is an estimate of the abundance of green sturgeon within the bay, and it may comprise a smaller fraction of the entire population of this largely oceanic species than that of the white sturgeon, which spends its life cycle within rivers and estuaries.

Most Important Issues

The Center for Biodiversity and Waterkeepers Northern California filed a petition with the National Marine Fisheries Service requesting an Endangered Species Act (ESA) listing of the green sturgeon as a threatened or endangered. This was based on a recent stock assessment (Musick *et al.*, 2000) that concluded that green sturgeon had suffered an 88% reduction in its abundance over its range. They argued that (1) spawning populations have been eliminated from five rivers on the northwestern coast of North America, (2) that the cumulative frequency of sturgeon captured in three fisheries in Washington State have declined over time, (3) existing size restrictions for commericial and sport harvest since these regulations are designed for white sturgeon, and the size limits are inclusive of breeding adults, (4) juvenile green sturgeon are killed in both the state and federal water export facilities, and (5) the effects of heavy metals and pesticides are unknown for green sturgeon.

A review of the status of the green sturgeon, commissioned by the State Water Contractors, concluded that populations of green sturgeon, though a relatively uncommon species, have remained constant in size over time, and that existing regulatory mechanisms may be adequate to protect the species (Beamesderfer and Webb, 2002). A preliminary elasticity analysis was carried out on green sturgeon, using catch data from the Columbia and Klamath Rivers and San Pablo Bay and other biological information, that indicated that the green sturgeon, like other late maturing, and long lived species, may be extremely susceptible to overharvest (Heppell and Hoffman, 2002). Reducing the range of sizes harvested, reduces the effect of harvest on the average growth rate and egg production. The majority of a committee of scientists from the National Marine Fisheries Service, which was aware of the two prior-mentioned reports, concluded that there is insufficient information to show the green sturgeon is in danger of extinction, or likely to become so in the near future (Adams *et al.*, 2002). They divided the population into two discrete units, a northern and southern population segment based on genetic studies. This decision was based on the absence of a negative slope to the catch or CPUE of spawning adults from the northern population in the Klamath River and a similar slope in estimates of the population of green sturgeon from the southern population in San Pablo Bay. However, a minority of this committee felt that though the southern population segment is presently not in danger of extinction, but is likely to become so in the near future. On 5 April 2005, the National Marine Fisheries Service reversed its decision, and filed with the Federal Register a proposed rule to list the green sturgeon south of the Eel River (the southern population segment) as threatened under the Endangered Species Act.

Suggested Targeted Research

The review committee indicated hat the southern population in the Sacramento/San Joaquin watershed faced more serious threats than the populations in the Klamath River and rivers farther north, including “concentration of spawning, smaller population size, lack of population data, potentially lethal temperature limits, harvest concerns, loss of spawning grounds, and entrainment by water projects, and influence of toxic material and exotic species”.

It is imperative to describe the distribution of spawning adults as well as to characterize their spawning habitat within the Sacramento River. This will provide insight into the degree of crowding of spawning adults and social consequences, the rates of egg and larval mortality, and the potential loss of this spawning habitat by anthropogenic changes in the system. The effect of thermal stress is known from laboratory tests, yet still unknown are the exact temperatures within the pools at which green sturgeon spawn. It is also important to sample both adults and juveniles over time within the system. We need to know what proportion of juveniles are lost due to entanglement in water diversion screens. Finally, the impact of toxic materials on the early life stages must be determined experimentally for different dosages, and surveys carried out within the river to determine whether levels of these pollutants are excessive, and can cause deletious effects to the young of the species.

Suggested Monitoring Activities

It is imperative that the Department of Fish and Game continue its bi-yearly surveys of white and green sturgeon in San Pablo Bay. Telemetric studies hold great promise. Individuals, carrying individually coded ultrasonic tags, tagged both in San Pablo Bay and other bays along the northwestern coast of North America, can be detected during their migration up various rivers by a series of tag-detecting monitors. Temperature loggers can be affixed to these monitors to provide a record of water temperature over time. Paired monitors and loggers can be placed at the junctions between the mainstem of the rivers and their tributaries as well as at large pools in reaches of the river. The physical environment can then be described at the locations, to which the adults migrate. Spawning can be verified by the deployment of spawning mats, which collect the eggs of the species. Much is already known about the basic biology of the species from laboratory studies. Once these field observations are completed, a large and comprehensive understanding the basic ecology of the species would permit the development of a population viability model, which could prioritize the above-mentioned risks to the population and guide management decisions.

Recognize Information Gaps

Although laboratory studies have yielded much information on the physiological needs of the species, field studies have yet to identify where adults spawn, particularly in the Sacramento River, and to provide a comprehensive description of the physical environment. Little is also known about the outmigration of juveniles, and their vulnerability to entrainment by water pumps and various pollutants.

Recognize Areas of Scientific Disagreement

The environmental community (e.g., Center for Biodiversity and Waterkeepers Northern California) believe that the species is threatened or endangered, and their opinions are not in agreement with the conclusions of a report (Beamesderfer and Webb, 2002), sponsored by the water users, and a species status review by NMFS (Adams *et al.*, 2002) that populations of the species are not in imminent risk of extinction. The development of a rigorous population viability model for the species, based on comprehensive laboratory and field observations, would likely lead to a resolution of this disagreement.

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